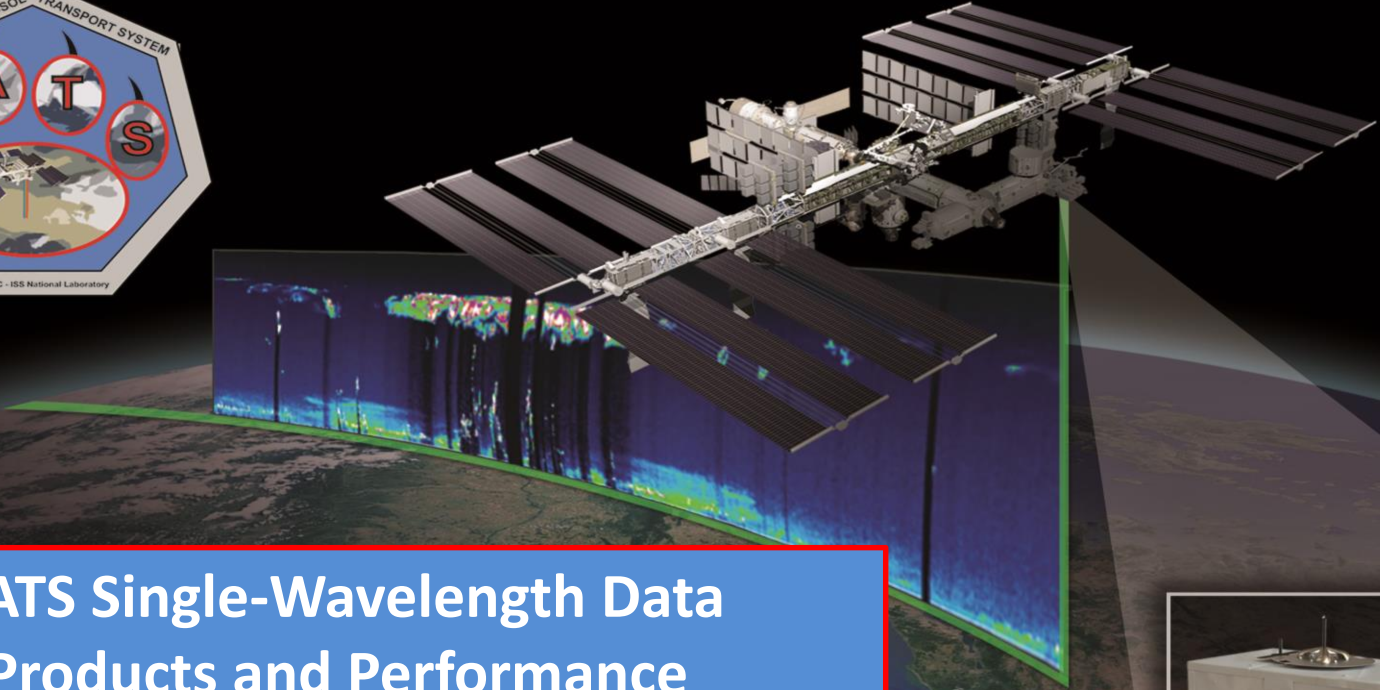

CATS Single-Wavelength Data Products and Performance

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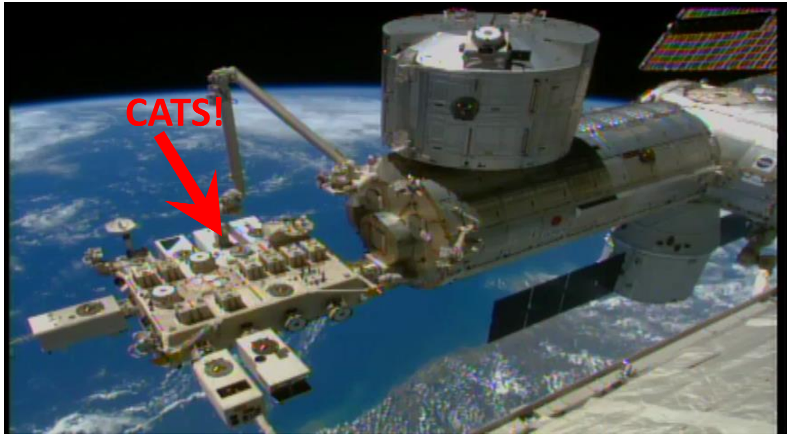
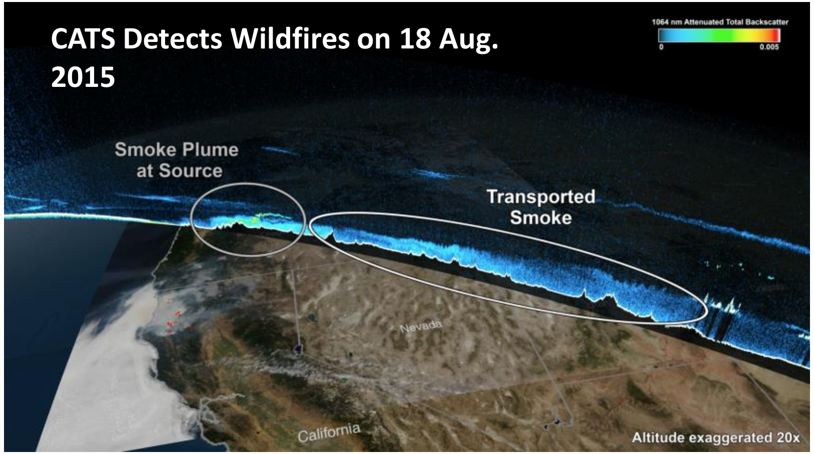
CATS Overview

- **CATS was designed as a tech demo (6 month lifetime) utilizing ISS as an affordable Earth Science platform to:**
  - **Complement CALIPSO data record w/ diurnally varying cloud/aerosol vertical profiles**
  - **Monitor dynamic events such as wildfires and volcanic eruptions**
  - **Provide in-space demonstration of technologies for future satellite missions**
  - **Demonstrate build-to-cost project development**
- **CATS operated on the ISS for 33 months and fired 200+ billion laser shots**



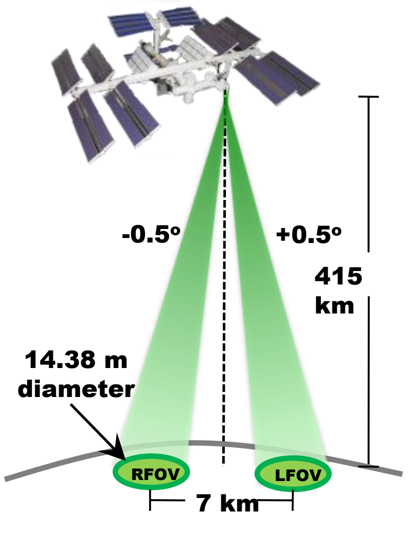


CATS Operation Modes

- **CATS demonstrated new technologies in space:**
  - Multiple beams separated by 7 km at surface (1.5 months of data)
  - First space-based measurements of depolarization at 1064 nm (& 2 wavelengths)
- **Early bumps in the road:**
  - Laser 1 failed 3/2015
  - Laser 2 couldn't be stabilized for HSRL retrievals (Mode 2)
- **Mode 7.2 1064 nm data was very reliable**
  - Operated in this mode for ~31 months so this talk will focus on this data
  - Suspected power/data system failure on 30 Oct. 2017 ended science operations

Mode 7.1: Multi-Beam

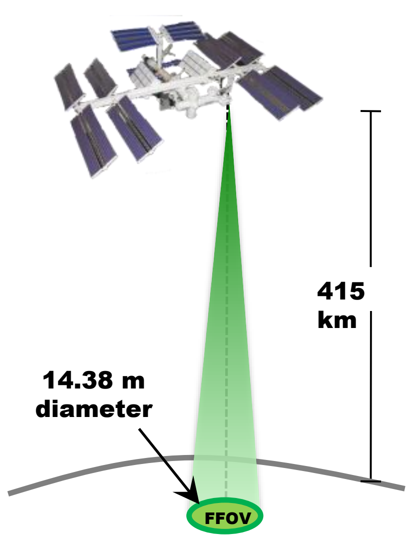
Backscatter: 532, 1064 nm
Depolarization: 532, 1064 nm
L2 Products: 532, 1064 nm



Semi-continuous operation:
Feb. 10 – Mar. 21 (2015)

Mode 7.2: Laser 2

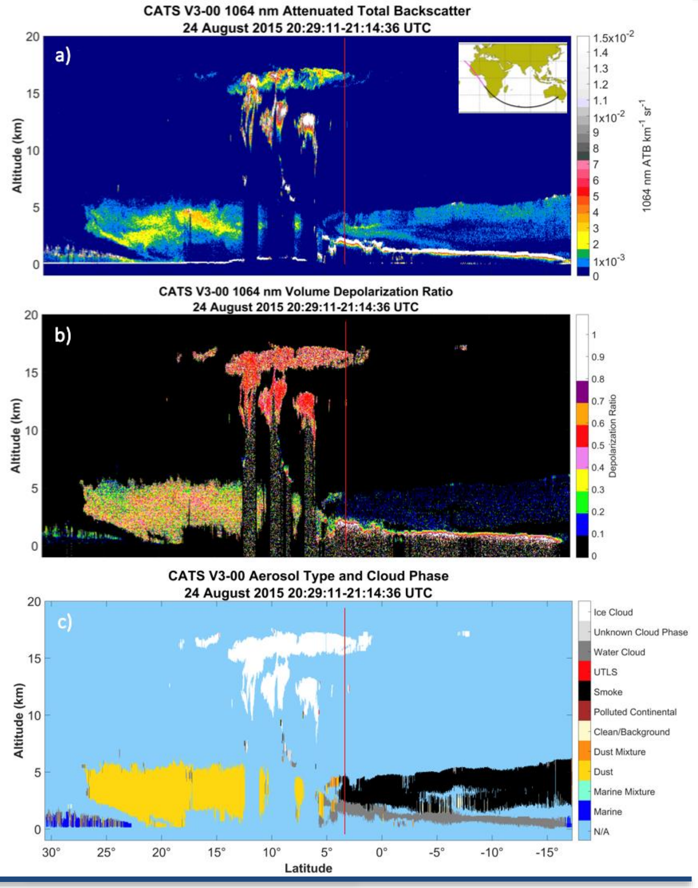
Backscatter: 532, 1064 nm
Depolarization: 1064 nm
L2 Products: 1064 nm



Semi-continuous operation:
25 Mar. 2015 – 30 Oct. 2017

CATS Mode 7.2 Data Products

- NASA GSFC and LaRC collaborated to incorporate lessons learned from CALIOP and make CATS products/browse images similar for lidar users
- Single-wavelength nature of Mode 7.2 required some new/different algorithms compared to CALIOP:
  - Level 1: Nighttime 1064 nm backscatter calibration directly using atmospheric profile instead of 1064-532 nm backscatter color ratio in cirrus clouds like CALIOP
  - Level 2: cloud-aerosol discrimination using horizontal persistence tests and other tests instead of backscatter color ratio, aerosol typing using GEOS information
- Several science applications, including
  - Long-range aerosol transport
  - Aerosol diurnal variability
  - Cirrus cloud diurnal variability



CATS 1064 nm Performance

The CATS Mode 7.2 nighttime 1064 nm clear-air SNR (red) is ~8X higher than that of CALIOP (dark green), enabling the CATS data to be calibrated directly using the atmospheric signal. This is due to:

1. **the higher CATS laser power**
2. **lower orbital height (415 km for CATS vs 705 km for CALIPSO)**
3. **photon counting/high laser repetition rate technique.**

The CATS Mode 7.2 daytime 1064 nm clear-air SNR (orange) is ~2X lower than CALIOP's (due to higher solar background noise), necessitating a different calibration technique for daytime data.

Pauly et al. [AMTD, 2019]

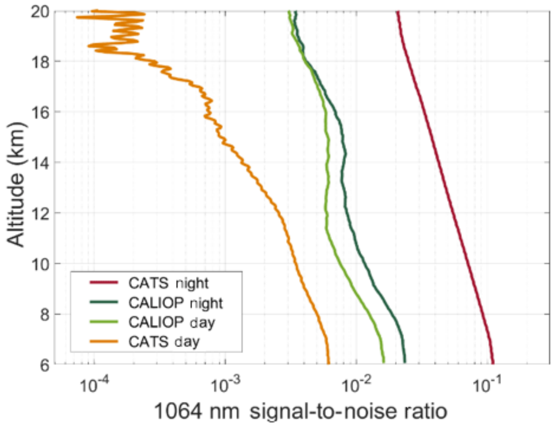


Table 1. CATS and CALIPSO 532 and 1064 nm Minimum Detectable Backscatter (MDB) With Units in Km^{-1} Sr^{-1}[a]

	CATS 7.1	CATS 7.2	CALIPSO
532 nm night	1.00E−3 ± 0.54E−3	1.60E−2 ± 0.84E−3	8.00E−4 ± 1.00E−4
1064 nm night	1.80E−4 ± 0.49E−4	5.00E−5 ± 0.77E−5	8.60E−4 ± 1.20E−4
532 nm day	2.20E−2 ± 0.35E−2	3.80E−2 ± 1.05E−2	1.70E−3 ± 0.30E−3
1064 nm day	7.60E−3 ± 0.24E−3	1.30E−3 ± 0.24E−3	1.00E−3 ± 0.30E−3

[a]CALIPSO values from *McGill et al.* [2007].

Yorks et al. [GRL, 2016]

MDB - weakest backscatter coefficient at which an atmospheric feature can be reliably detected. In the table below, the CATS MDB, is computed for cirrus clouds at 15 km with horizontal resolution of 5 km (vertical resolution of 60 m)

CATS Mode 7.2 nighttime data at 1064 nm has lower MDB than CALIOP, given SNR above.

CATS Mode 7.2 daytime data at 1064 nm has very similar MDB to CALIOP, despite the lower SNR, due to the low magnitude of 1064 nm molecular signal.

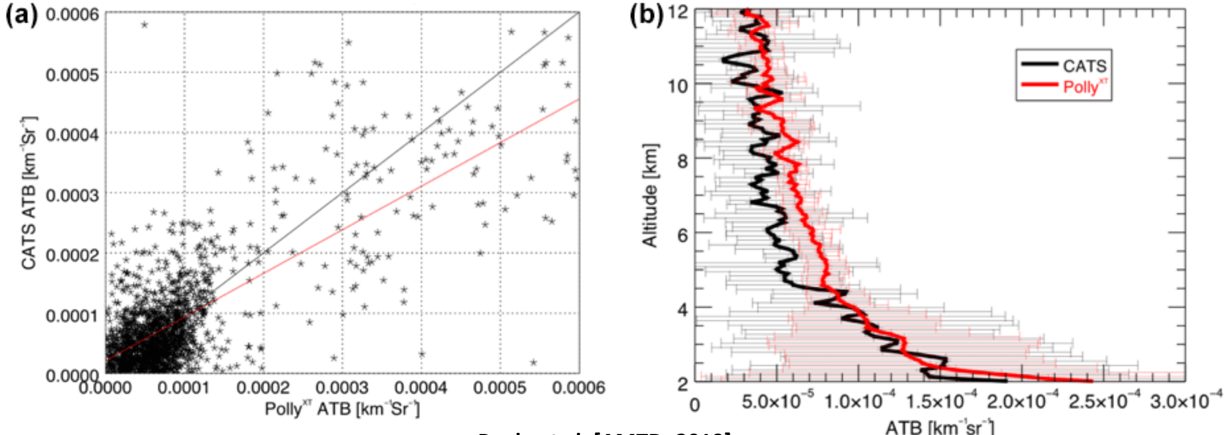
CATS 1064 nm Calibration: Nighttime

Nighttime CATS Mode 7.2 data were calibrated by scaling the measured data to a model of the expected atmospheric backscatter (molecular backscatter from MERRA-2 and aerosol scattering ratios from CALIOP) between 22 and 26 km.

$$C_\lambda(r) = \frac{\left[\dfrac{\mathrm{NRB}(r)}{T_\mathrm{O}^2(r)R(r)}\right]}{\beta_\mathrm{M}(r)\,T_\mathrm{M}^2(r)} = \frac{\beta_\mathrm{CN}(r)}{\beta_\mathrm{M}(r)\,T_\mathrm{M}^2(r)}.$$

$$\left(\frac{\Delta C}{C}\right)_\mathrm{sys} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\frac{\Delta\beta_\mathrm{M}}{\beta_\mathrm{M}}\right)^2 + \left(\frac{\Delta T_\mathrm{M}^2}{T_\mathrm{M}^2}\right)^2 + \left(\frac{\Delta\chi_\mathrm{P}}{\chi_\mathrm{P}}\right)^2}.$$

CATS nighttime 1064 nm calibration technique uncertainties are ~9%, primarily due to the high aerosol scattering ratio uncertainties in the 22-26 km region and assumptions about the backscatter color ratios of these aerosols.



Pauly et al. [AMTD, 2019]

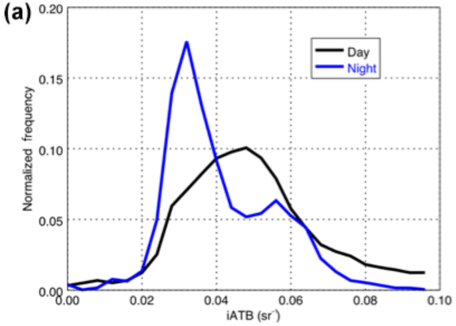
CATS ATB was ~19% lower compared to PollyXT in 8 nighttime clear-sky cases over the Leipzig, Germany with a correlation coefficient of 0.75. CATS ATB was ~7% lower for PBL aerosols over the same site.

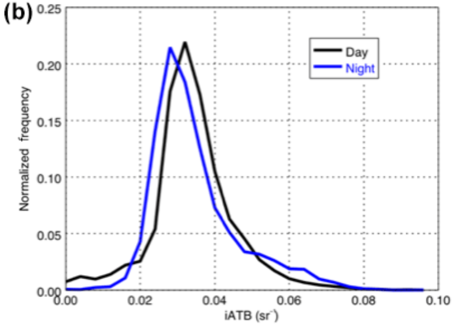
CATS 1064 nm Calibration: Daytime

Daytime CATS Mode 7.2 1064 nm data were calibrated through comparisons with nighttime measurements of the layer-integrated ATB from strongly scattering, rapidly attenuating opaque cirrus clouds (bottom left).

$$C_{\text{day}} = \frac{1}{N_{\text{day}}} \sum_{k=1}^{N_{\text{day}}} \text{iNRB}_k \Big/ \frac{1}{N_{\text{night}}} \sum_{k=1}^{N_{\text{night}}} \text{iATB}_k ,$$

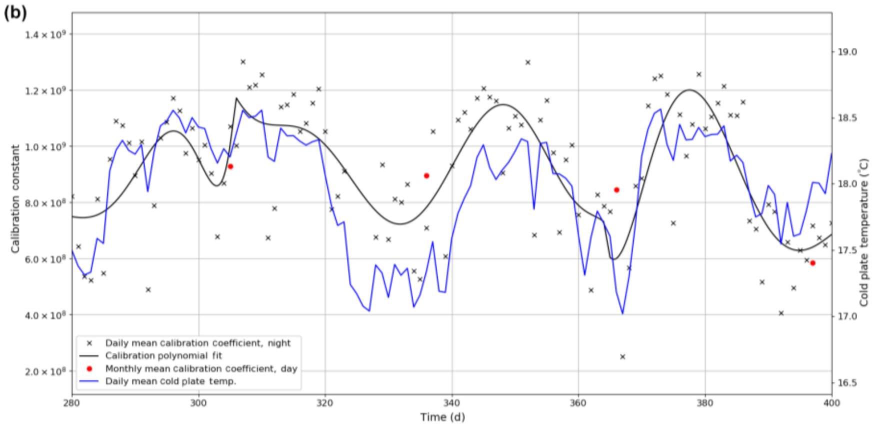
The daytime calibration uncertainty is estimated as 16-18%, due to the variability of the NRB signal (random signal noise) and the nighttime calibration error.





The CATS 1064 nm nighttime calibration coefficients (black line) fluctuate over a period of 30-40 days, correlated with the thermal stability of the cooling loop on the ISS (blue line).

The daytime calibration coefficients (red dots) also fluctuate with thermal stability.



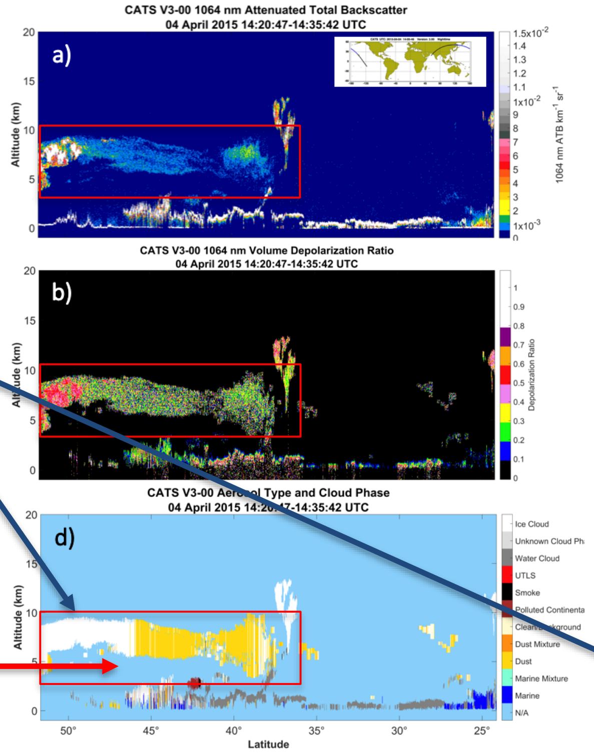
Pauly et al. [AMTD, 2019]

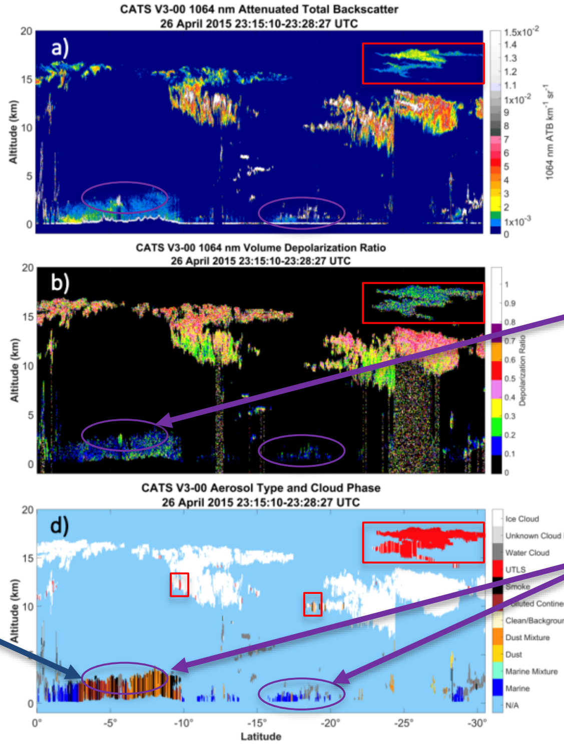
CATS Feature Typing

- **The CATS Cloud-Aerosol Discrimination (CAD) multidimensional PDF algorithm performs well, with 2 exceptions:**
  1. **UTLS aerosols: Under-represented in the CPL data used for the CATS CAD multidimensional PDFs**
  2. **Complex mixtures of clouds and aerosols in the PBL: Mode 7.2 CATS lacks backscatter color ratio used in CALIOP for differentiating these features.**

CATS uses a Horizontal Persistence Test implemented in daytime differentiate clouds and aerosols

CATS uses tropopause height, ATB/depol, and a Relative Humidity Test to better identify dust layers lofted into the UTLS





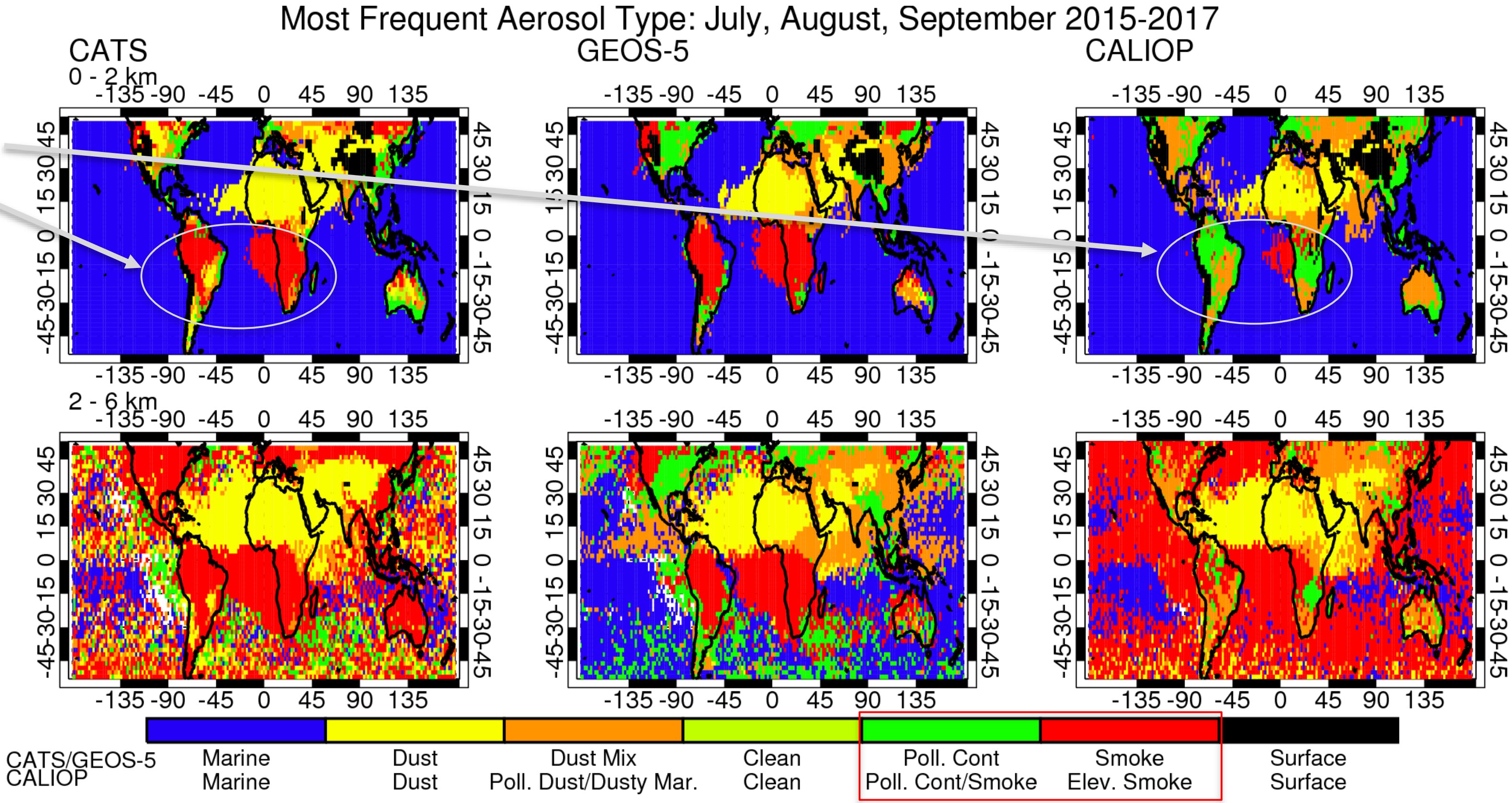
CATS uses an Integrated Perpendicular Backscatter Test to detect clouds/aerosols in the PBL since multiple scattering from ice and liquid water clouds results in layer-integrated perpendicular backscatter values that are significantly higher than aerosols

CATS uses a Cloud Fraction Test to detect aerosol layers that have clouds (high ATB spike) embedded by using the 350 m data to detect small-scale clouds

CATS Aerosol Typing

CATS and CALIOP have different Smoke & Polluted Continental definitions

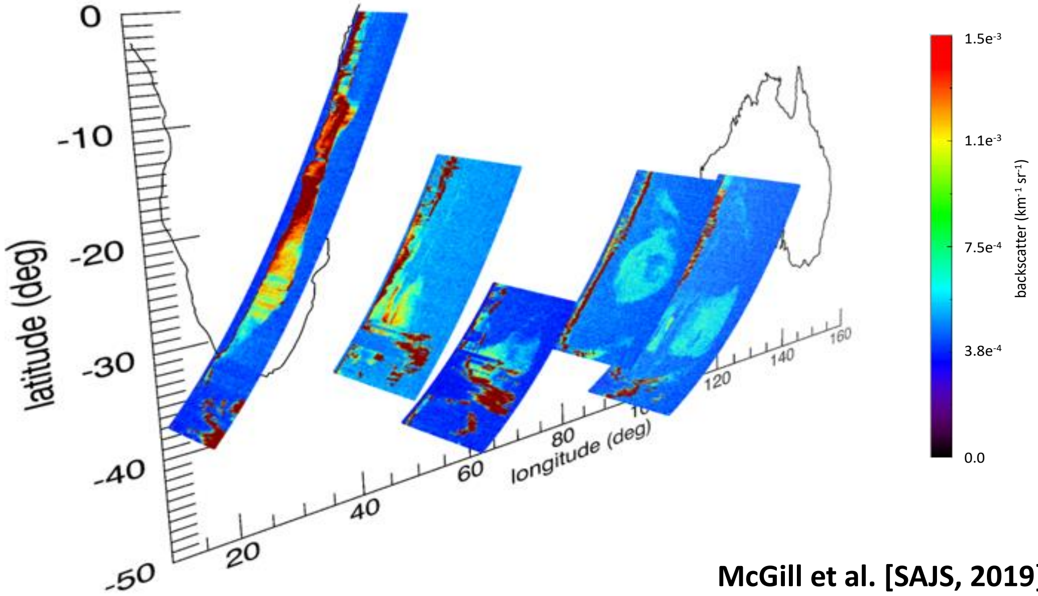
Differences in Dust & Dust Mix types due to depolarization thresholds and wavelengths



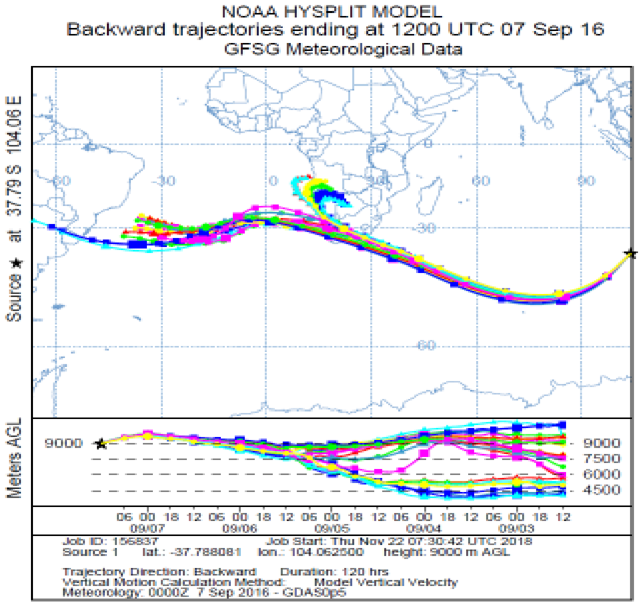
Long-Range Aerosol Transport

CATS observed several cases of long-range smoke transport from Africa across the Indian Ocean, quantifying evolution of loading and vertical distribution.

Shown below is one example from 07 Sep. 2016. The elevated layer near Australia is distinct and extends from 3 - 11 km, but AOD is only 0.04 +/- 0.008. The layer starts with higher AOD (0.15 +/- 0.05) over Africa.



McGill et al. [SAJS, 2019]

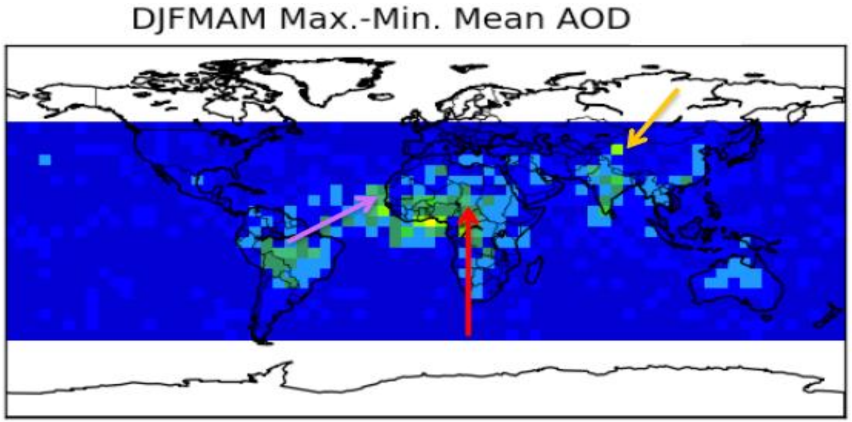


Aerosol Diurnal Variability

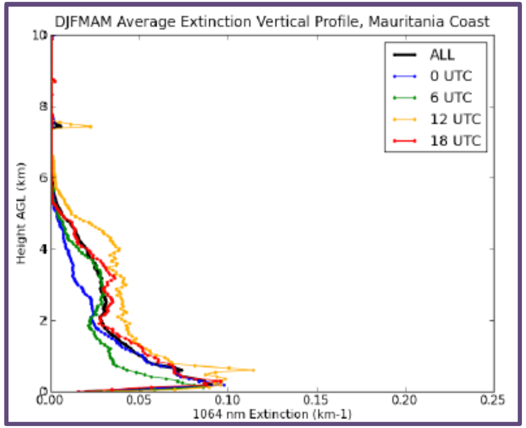
CATS data shows the diurnal variability of aerosol properties, depending on season/region, can be significant:

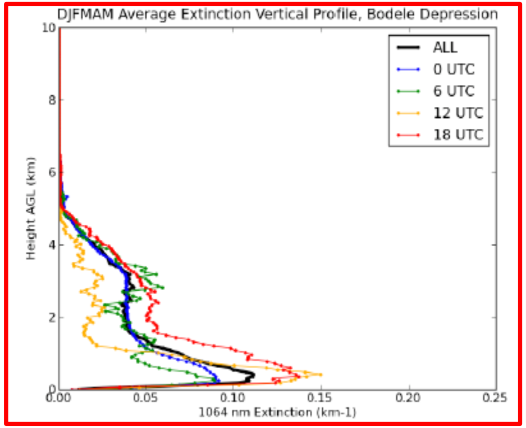
Lee et al. [ACPD, 2019] found diurnal variability of extinction as high as 0.10 km^{-1} in Sahara and Sahel regions in Africa, and Tarim Basin in Asia (shown here).

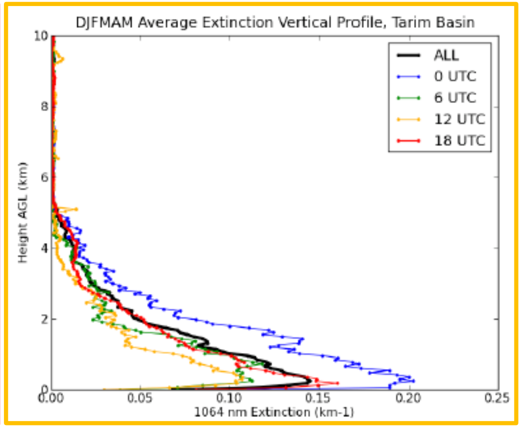
Yu et al. [ACPD, 2019] found diurnal variability of Dust AOD in numerous regions (next talk!).



A-Train sensors are not capturing this variability and geostationary sensors cannot capture the vertical profile.



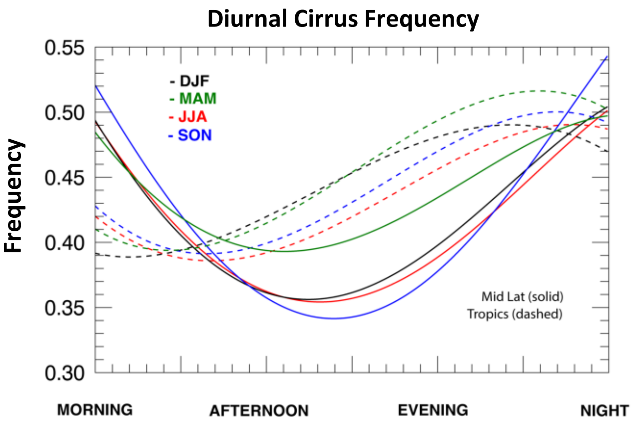


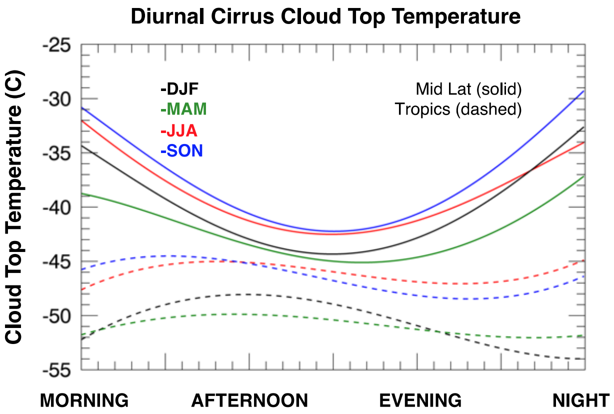


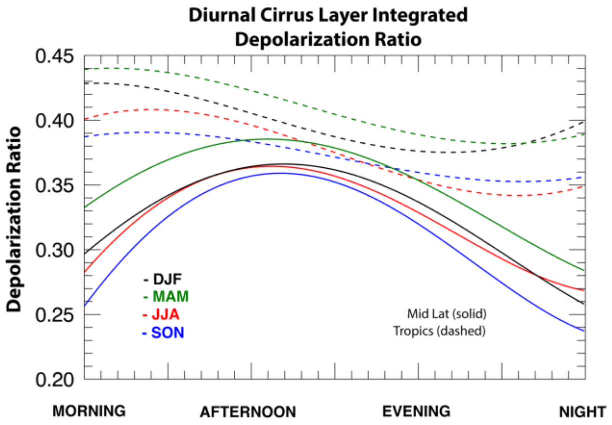
Cirrus Cloud Diurnal Variability

Mid-Latitude Cirrus: More frequent at night (>50%), which agrees with Noel et al. [ACPD, 2018], but have warmer temperatures (-30 C) and lower depolarization ratios (~0.25) at that time. Daytime cirrus, while less frequent (~35%), have higher depolarization ratios (>0.35) and colder cloud top temperatures (-45 C).

Tropical Cirrus: Most frequent in evening (>50%) with lowest frequencies in the morning hours due to afternoon convection. Diurnal variability of cloud top temperature and depolarization ratios is smaller compared to mid-latitude cirrus clouds.







Summary

- CATS single wavelength 1064 nm algorithms utilize new features compared to a multiple wavelength system.
  - Calibrate 1064 nm signal directly using the atmospheric normalization technique, typically used at 532 nm
  - Use additional tests to better differentiate cloud and aerosol features
  - Utilize other space-based datasets (CALIOP, etc.) and models (GEOS, etc.) to improve calibration and aerosol typing
- While two wavelengths are ideal for some science applications, CATS Mode 7.2 data has shown that a single wavelength lidar at 1064 nm can provide important data products for several other science applications:
  - Above Cloud Aerosol: Robust 1064 nm data improves near-IR retrievals and can help improve layer detection for cases such as smoke layers from biomass burning in the SE Atlantic above stratocumulus decks: Rajapakshe et al. [GRL, 2017]; Lu et al. [PNAS, 2018].
  - Diurnal Variability: Significant diurnal variability of cloud and aerosol vertical profiles exists on regional/seasonal scales that is not captured by the sun-synchronous sensors due to sampling times: Noel et al. [ACPD, 2018]; Lee et al. [ACPD, 2019]; Yu et al. [ACPD, 2019]; Dauhut et al. [ACPD, 2019]
  - Long-Range Aerosol Transport: The CATS 1064 nm signal with high SNR more accurately detects tenuous aerosol layers that have been transported over long distances: Chen et al. [JAE, 2018]; Vaughan et al. [ACPD, 2018]; Stachlewska et al. [JRS, 2018]; McGill et al. [SAJS, 2019].
  - Modeling Aerosol Transport: NRT space-based lidar data enables assimilation into aerosol forecast models for improved vertical structure and has a big impact on forecasting and monitoring hazardous events (i.e. volcanic eruptions and wildfires): Hughes et al. [GRL, 2016].
- Special thanks to:
  - ISS Program (HEOMD) for funding the instrument
  - NASA SMD for funding algorithms/data products (joint w/ LaRC)
  - ROSES CCST 2015 for CATS-CALIPSO comparisons and analysis of aerosol properties

To download CATS data, visit http://cats.gsfc.nasa.gov/data/browse or the ASDC Website